Silicon Pixel and CCD Tracking Detectors

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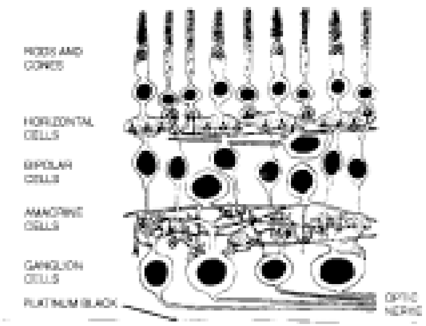
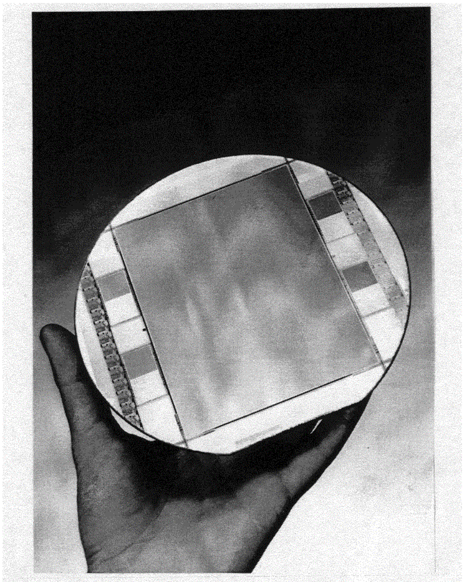
10 July, 2001
SNOWMASS

- Physics motivation
- Why silicon?
- Why pixels?
- Technology options
- Track record (physics)
- The future (at the energy frontier)
- Other applications

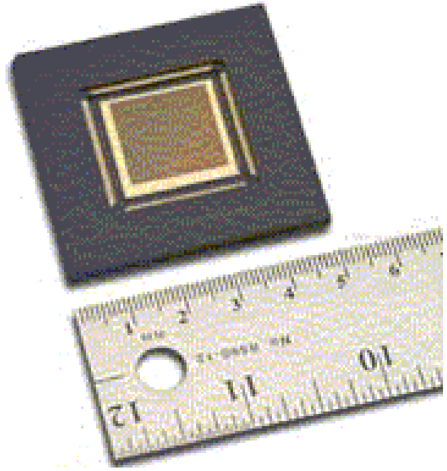
- Pixel detector: a device having a matrix of photo-sensitive sites which can be interrogated to assemble a 2-D image or picture



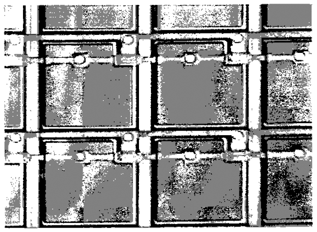
Retina 100×10^6 pixels



CCD - Philips
63×10^6 pixels 12×9 cm^2

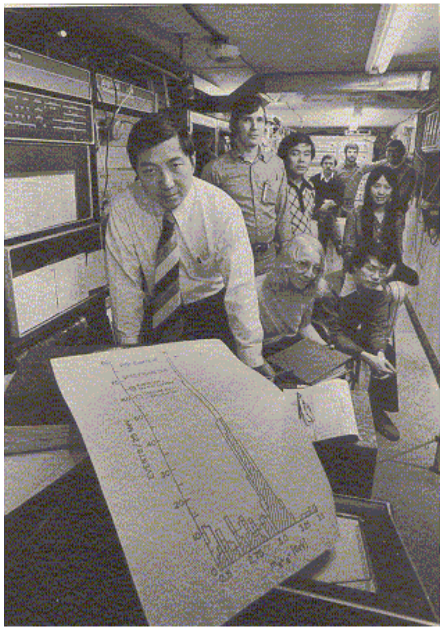


CMOS imager – Foveon
16×10^6 pixels 1.5×1.5 cm^2



Amorphous silicon imager – Xerox
7.4×10^6 pixels 29×41 cm^2

- For particle tracking, generally require point measurement precision $\lesssim 10\mu m$, so we ignore detectors with relatively large pixels ($\gtrsim$ 1 mm)



Physics Motivation November Revolution

J/ψ

11 November 1974

- Gaillard, Lee and Rosner RMP **47** (1975) 277 *Search For Charm*
  'The tracks of charmed particles will be too short to see in bubble chambers, but should definitely be of the order of tens or hundreds of microns: easily detectable in emulsion'.
- Charpak, EPS Conference in Palermo June 1975
  'Drift chambers are the easiest to build, most accurate, cheapest and most convenient detector for localising particles. Whoever is familiar with their operation would be strongly reluctant to use other devices in the planning of a new experiment'.
- ACCMOR collaboration in CERN struggled to see charm hadroproduction (single *e* trigger)
- Succeeded over next 10 years to develop silicon microstrip and pixel detectors (CCDs) as powerful tools for charm physics.

The first pixel detector used for particle physics had already been invented 5 years before charm was discovered, with very different applications in mind …

Charge Coupled Semiconductor Devices

By W. S. BOYLE and G. E. SMITH

(Manuscript received January 29, 1970

In this paper we describe a new semiconductor device concept. Basically, it consists of storing charge in potential wells created at the surface of a semiconductor and moving the charge (representing information) over the surface by moving the potential minima. We discuss schemes for creating, transferring, and detecting the presence or absence of the charge.

In particular, we consider minority carrier charge storage at the Si-SiO_2 interface of a MOS capacitor. This charge may be transferred to a closely adjacent capacitor on the same substrate by appropriate manipulation of electrode potentials. Examples of possible applications are as a shift register, as an imaging device, as a display device, and in performing logic.

Bell System Technical Journal, **49** (1970) 587

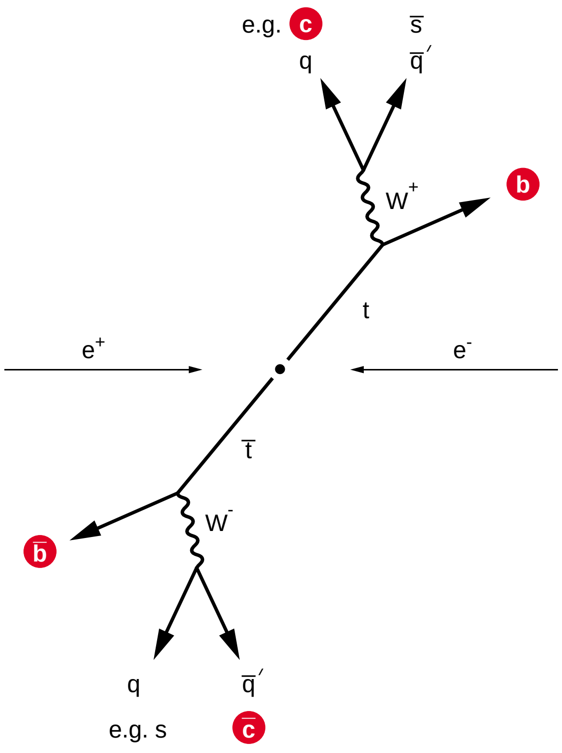
Physics Motivation Today

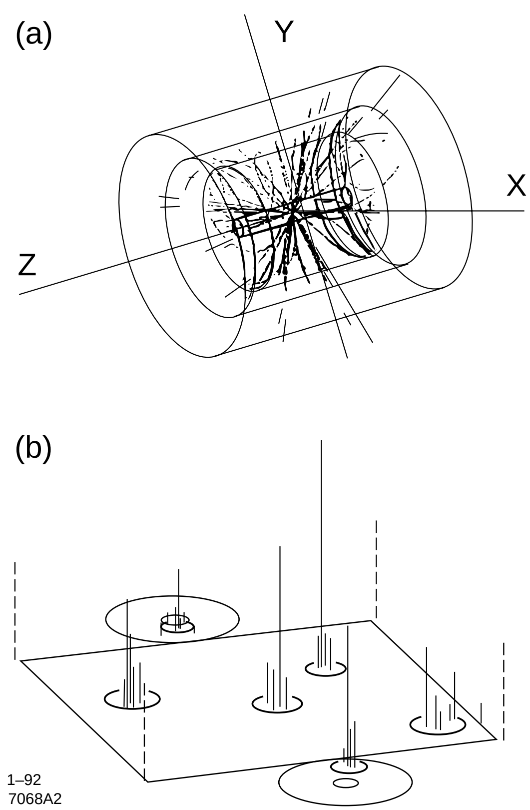
A few examples:

- BTeV (when funded!) will use pixel detectors for a level-1 vertex trigger, accumulating unprecedented samples of B mesons and baryons

- Pixel-based vertex detectors are needed at LHC for many physics purposes, eg $h \to b\bar{b}$

- Multi-jet processes at the future LC



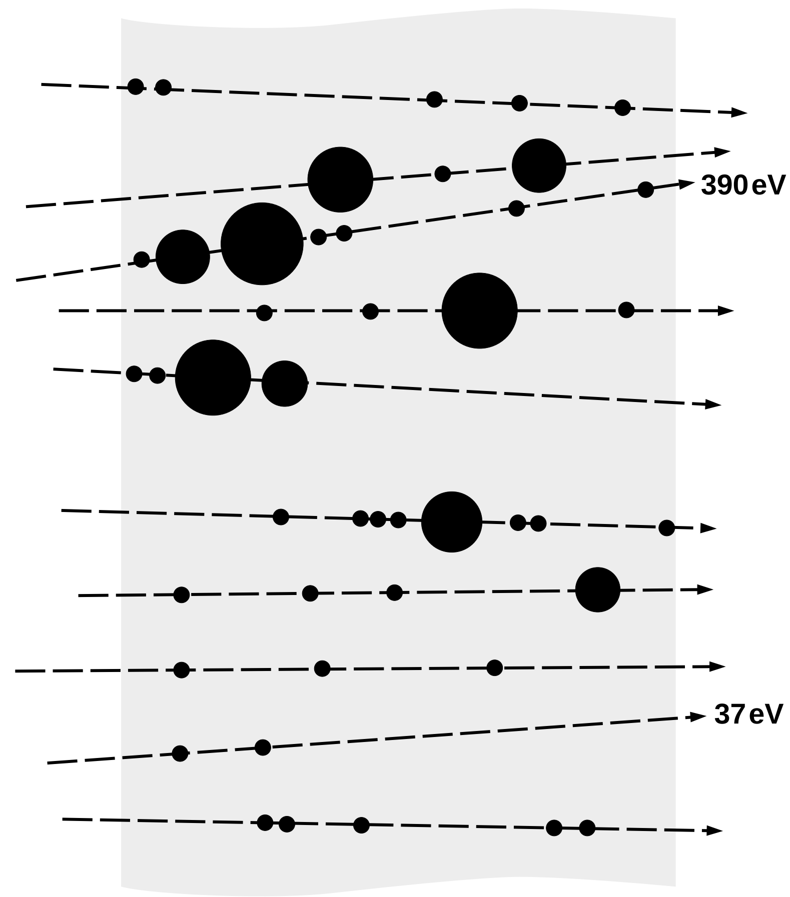


Why Silicon?

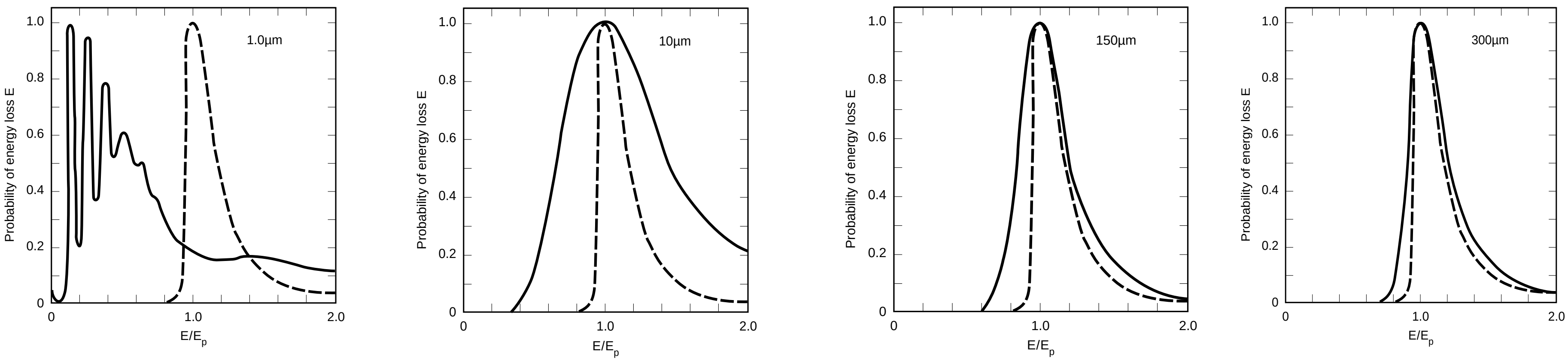
- Gaseous detector (eg argon): ionisation potential 15.7 eV
- Crystalline silicon band gap 1.1 eV, yielding 80 e-h pairs/μm of min-I particle track
- Less than 0.1% of ejected electrons have range above 1 μm in silicon
- Potential for 'electronic nuclear emulsion'
- The highly developed *planar process* for IC manufacture: a marvellous flow of structures for use in detectors
- [The *bad old days* of unreliable home-made surface barrier detectors are fortunately long gone]

Charge generation process:

- 3.2 M-shell plasmons per μm (17 eV)
- 0.6 L-shell electrons per μm (120 eV)
- 10^{-2} K-shell electrons per μm (1.5 keV)
- plus associated Auger electrons
- overall ~ 4 primary collisions per μm with widely fluctuating energy loss
- final thermalisation yields *on average* one e-h pair per 3.6 eV deposited



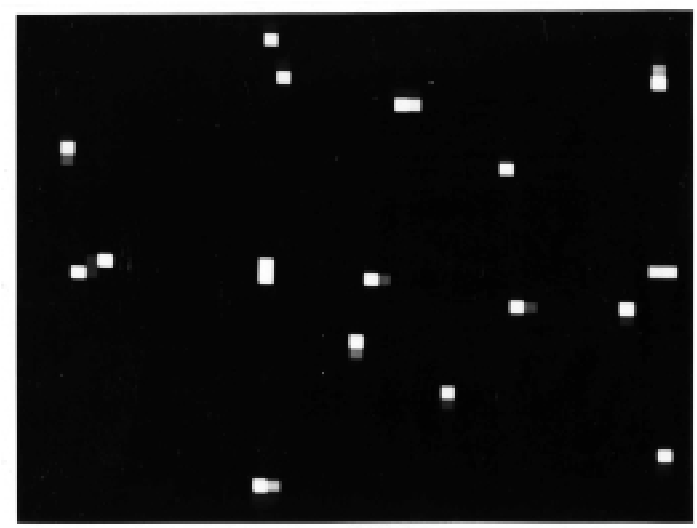
- For efficient min-I particle detection, be careful not to go *too* thin:

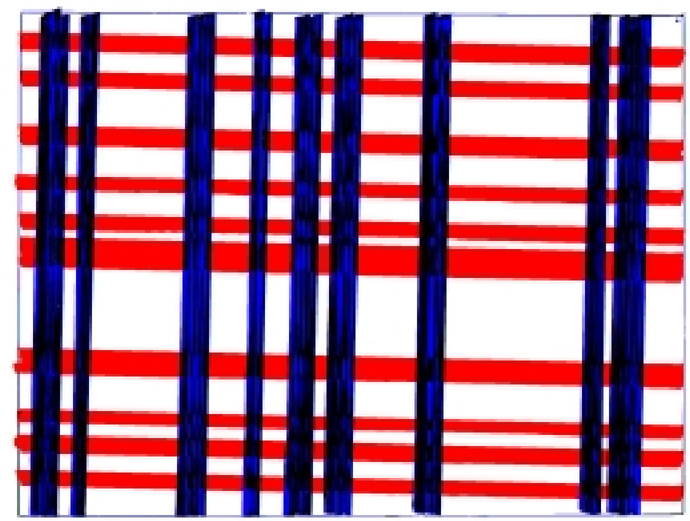


1 μm **10 μm** **150 μm** **300 μm**

- Need surprisingly low threshold for efficient min-I detection from a thin detector
- By 300 μm thick, conventional Landau distribution is quite accurate
- See 'CCDs as particle tracking detectors, C Damerell, Rev Sci Instr 64 (1998) 1549, and references therein, notably Hans Bichsel's Rev Mod Phys paper on energy loss in silicon.

Why Pixels?

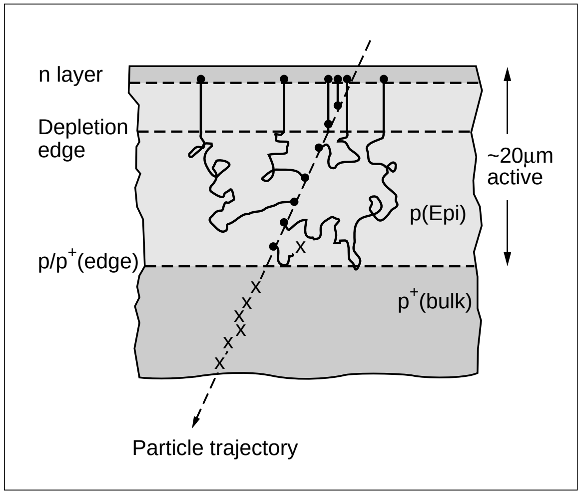




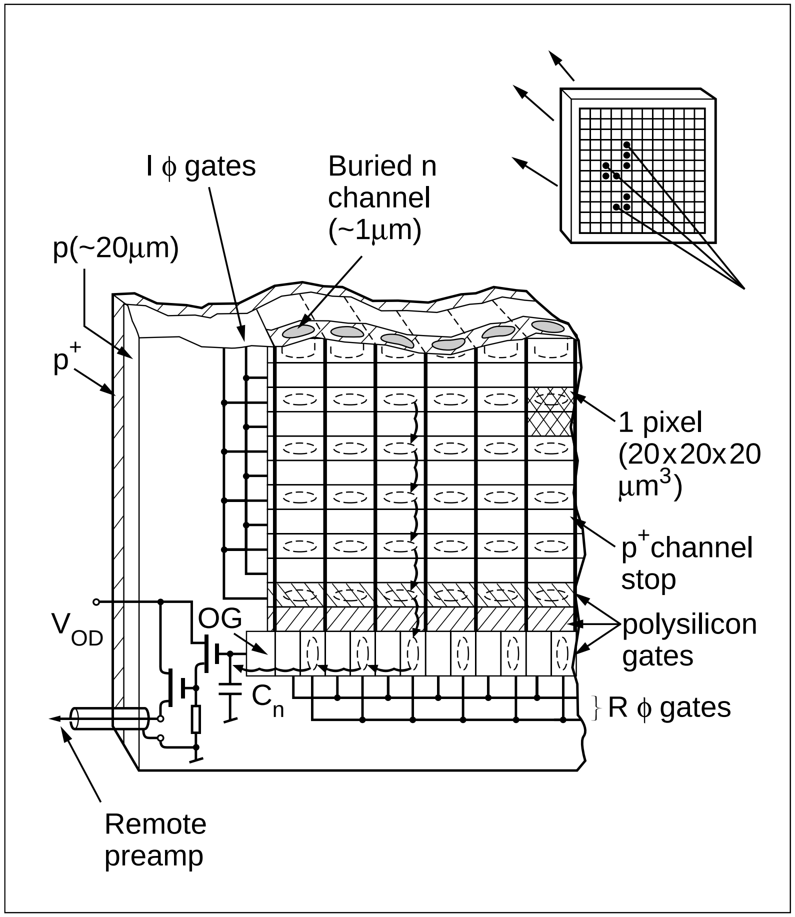
- Vertex detector performance depends on getting first layer close to IP
- High hit densities inevitable in the core of high energy jets
- $1\,\mathrm{mm}^2$ of CCD detector in CERN test beam in 1980
- Compare performance of hypothetical 2-D microstrip with $20\mu\mathrm{m}$ pitch
- 17 hits should create $17^2 = 289$ candidates in microstrip equivalent, but see only 90

Technology Options

Charge-coupled devices (CCDs), monolithic active pixel sensors (APS) and hybrid APS

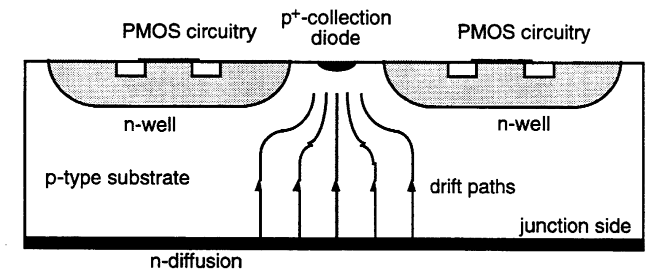


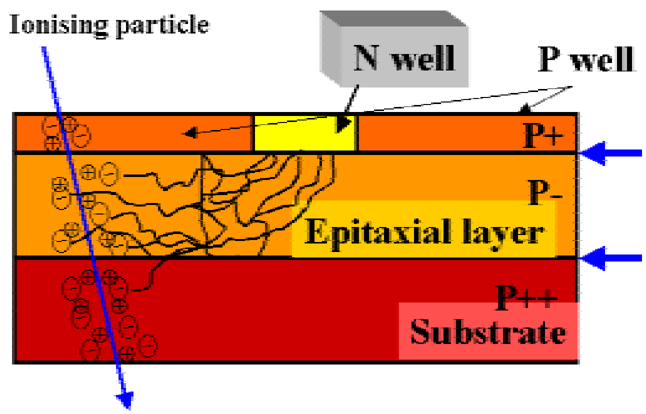
CCDs

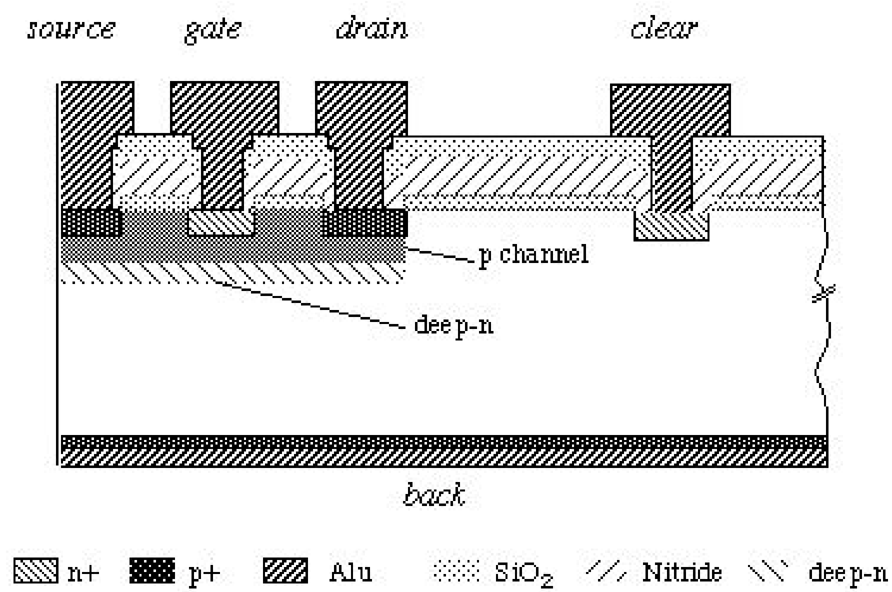


- On-chip source follower (C_N ~10fF) provides < 100 e^- rms noise at > 10 MHz pixel rate
- High inter-pixel uniformity:
  star trackers achieve < 0.1 μm precision
- Recent developments and suggestions:
  - LLL CCD: noise reduced to < 1 e^- rms
  - Column parallel CCD; may reduce frame readout time by factor 100 to 1000

Monolithic APS

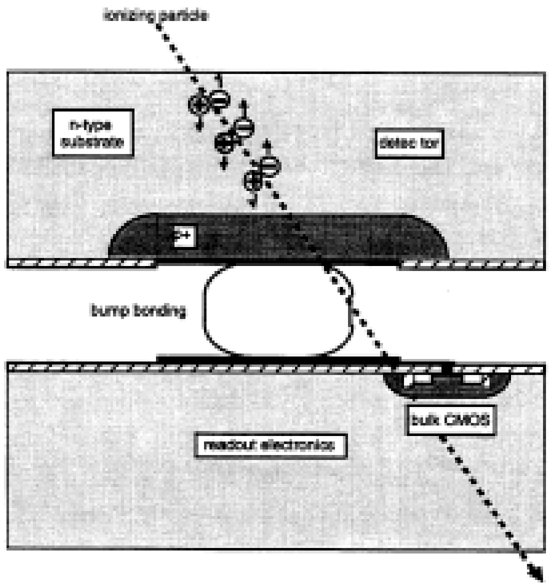


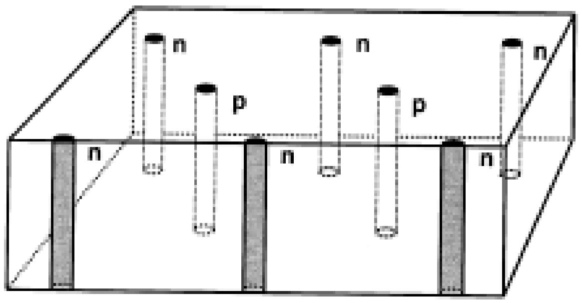




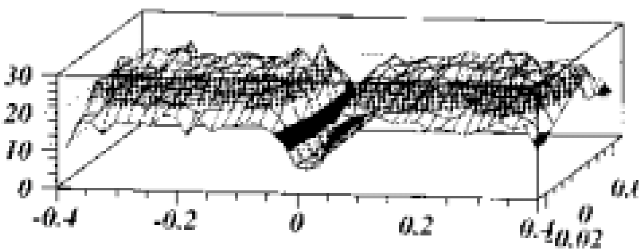
- Signal charge is sensed by front-end electronics within each pixel
- Each row is addressed in turn, connecting their outputs to column buslines, and peripheral logic
- Potentially more radiation resistant than CCD, due to avoidance of charge transfer losses

Hybrid APS

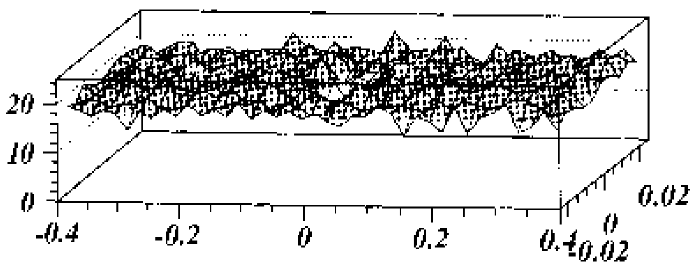




Hawaii group (3-D)



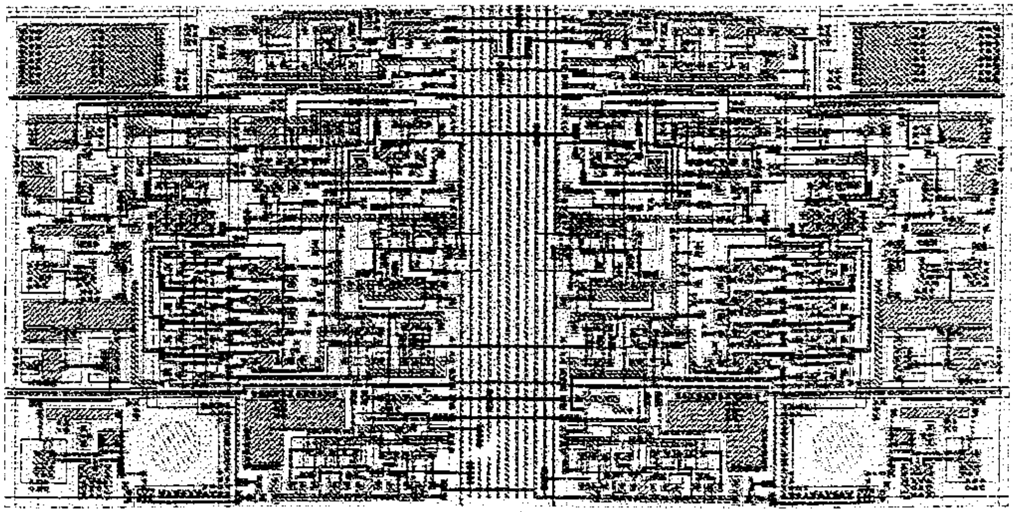
ATLAS atoll problem



ATLAS problem fixed

- Fast charge collection (fully depleted detector)
- 'standard' detector design is far from trivial, and 3-D version is front-ranking R&D

Readout chip (example from CMS)



CMS PUC pair

- Fully flexible CMOS readout chip: 120 transistors and 7 capacitors per pixel in $125\times125\mu m^2$

- In-pixel comparator triggers:
    - local storage of analogue pulse height
    - prompt signal on column busline to periphery
- BX number stored in *time-stamp buffer* on periphery
- During next 6-8 BX, scan all pixels in the double column
- When hit pixels are found, transfer pulse heights and row addresses to peripheral *data buffer*

- Advantages are phenomenal time resolution and radiation hardness

[New: ATLAS analogue blocks good beyond 61 Mrads]

- Disadvantages are large area pixels, power dissipation and thickness
- Bump bonding goes beyond typical industrial capability: still significant challenges

Pixel/CCD Tracking Detectors

Technology	Example Experiments	Pixel size	Active thickness	Layer thickness
		$(\mu m)^2$	μm	$\% X_0$
CCD	SLD Future LC	20×20 20×20	20 20	0.4 0.06
Monolithic APS	Hawaii Strasbourg/RAL RAL MPI/Bonn	125×34 20×20 25×25 50×50	300 14 only 5 300	
Hybrid APS	WA97 ATLAS	500×75 300×50	300 250	1.7 1.7

Technology	Device size		Detector size	Tracking Precision	Time resolution	Expt/ Comments
	Pixels	mm^2	Mpixels	μm		
CCD	3.2×10^6 7.5×10^6	80×16 125×24	307 800	< 3.5 < 3.5	150 ms 50 μs	SLD FLC[Col parallel]
Monolithic APS	10×30 64×64 525×525 64×64	1.25×1.0 1.28×1.28 13.1×13.1 3.2×3.2		2.0 1.6	100 ms	Test beam Test beam In design X-ray imaging
Hybrid APS	1392 18×160	9×5.8 5.4×8	0.71 100	24 15	25 ns	WA97 ATLAS

Deep Submicron CMOS Technology

- Use of ASICs in readout systems (initially microstrips) pioneered by Bernard Hyams and Sherwood Parker around 1980 - obligatory for all collider detector applications

- Deep submicron CMOS - a fast-moving technology which underpins most current developments. All pixel detector systems are real or potential beneficiaries

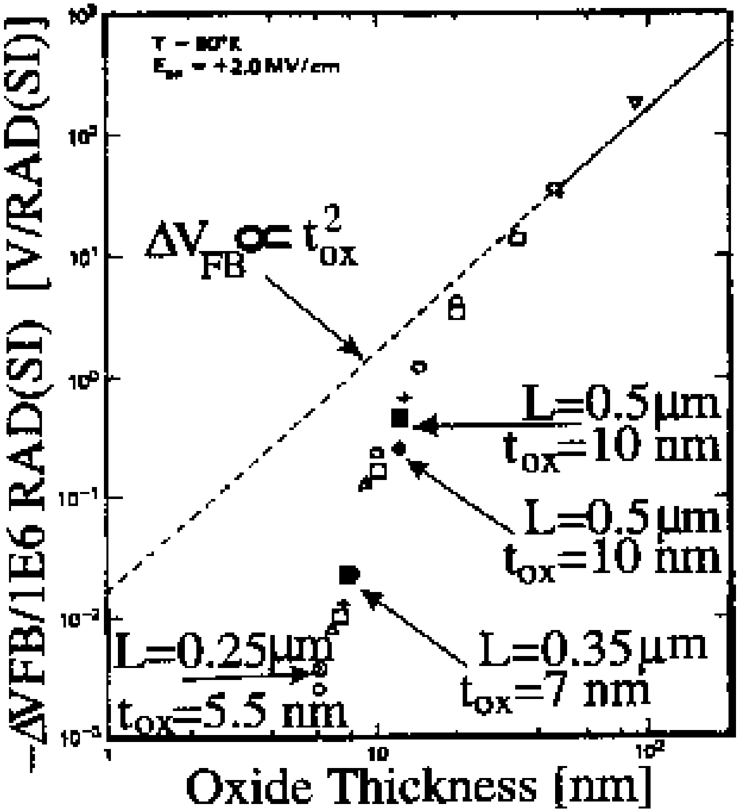
- 3 main aspects:

  - reduced feature size, so more powerful functionality per pixel

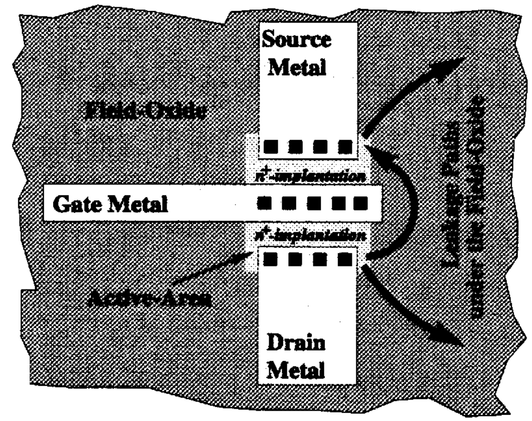
  - multi-layer metal. Step coverage no longer an issue *[Damascening]*

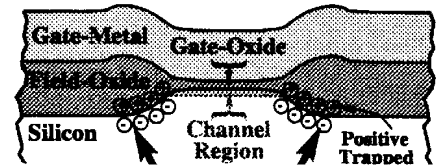
  - radiation resistance due to thin dielectric and ring transistor designs (> 30 Mrad)

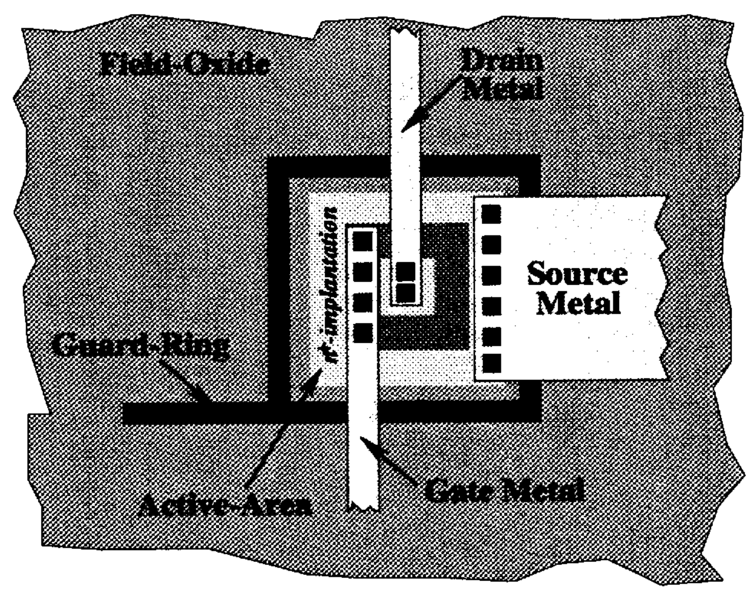
- Other rad hard technologies (eg Bi-CMOS SOI) have yield problems and/or are becoming less readily available.


T = 80°K
E_{ox} = +2.0 MV/cm
$\Delta V_{FB} \propto t_{ox}^2$
L=0.5µm
t_{ox}=10 nm
L=0.5µm
t_{ox}=10 nm
L=0.25µm
t_{ox}=5.5 nm
L=0.35µm
t_{ox}=7 nm
−ΔVFB/1E6 RAD(SI) [V/RAD(SI)]
Oxide Thickness [nm]

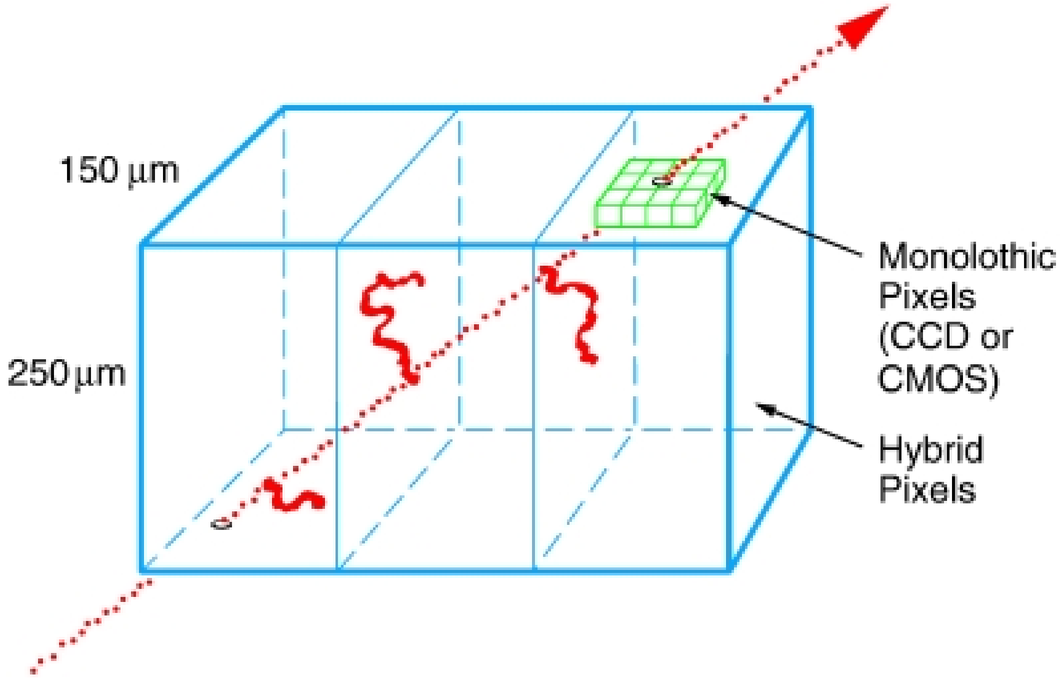
Saks 1984


Source
Metal
Field-Oxide
n^+-implantation
Gate Metal
n^+-implantation
Active-Area
Drain
Metal
Leakage Paths
under the Field-Oxide


Gate-Metal
Gate-Oxide
Field-Oxide
Silicon
Channel
Region
Positive
Trapped


Field-Oxide
Drain
Metal
n^+-implantation
Source
Metal
Guard-Ring
Active-Area
Gate Metal

Technology Options: the bottom line



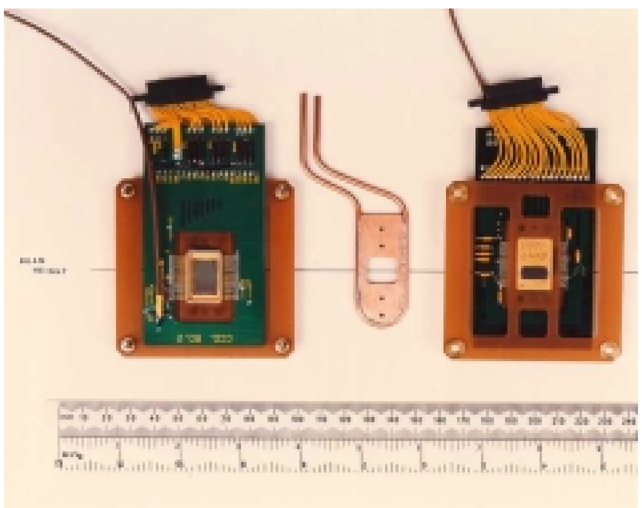
- If high speed and/or radiation resistance demand them, must use hybrid pixels
- If environmental conditions permit, use CCDs (or in future possibly monolithic APS) for higher tracking precision and hence greater physics capability
- [Applies in general only if the desired physics performance is beyond reach, which is the case in all existing and planned vertex detectors]

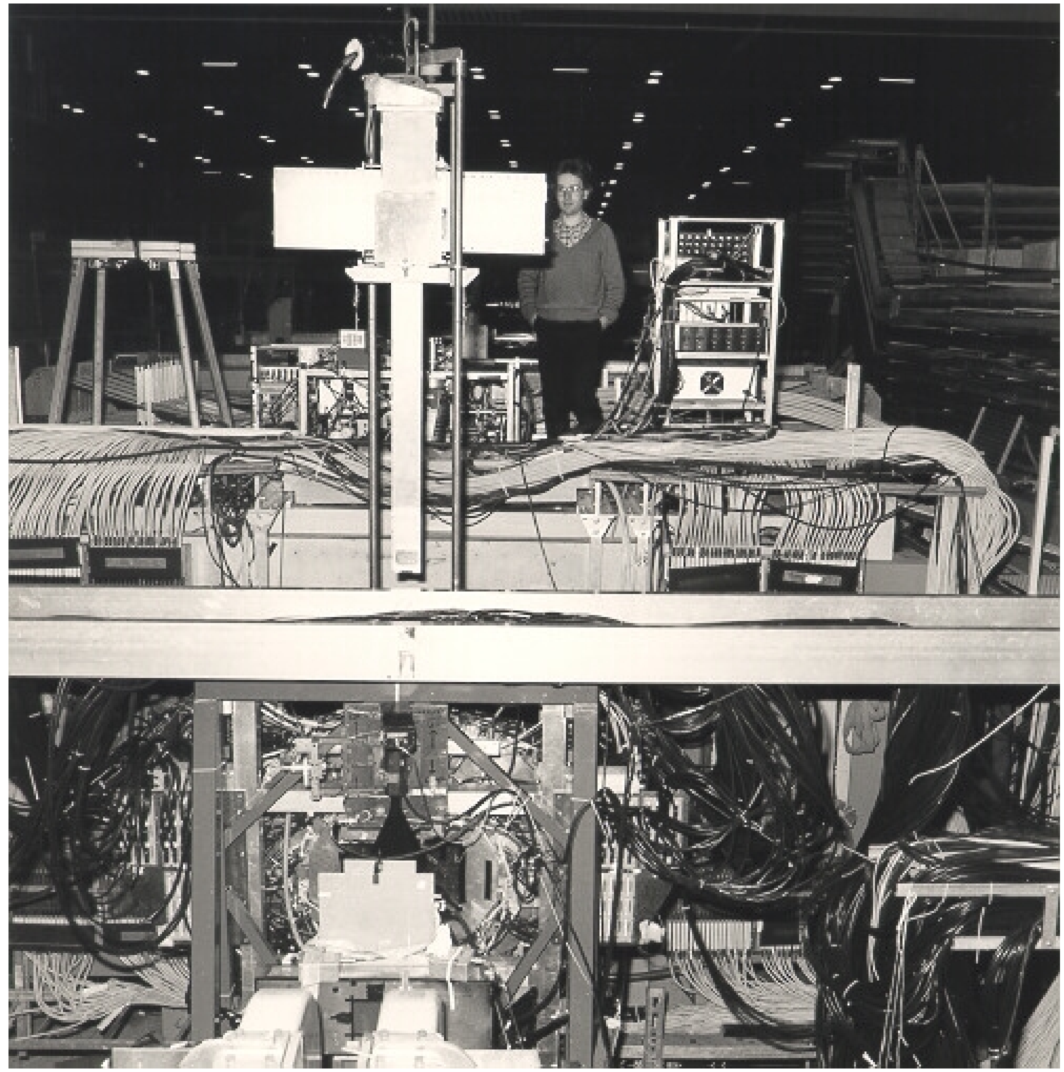
Track Record for Physics

Experiment NA32 at CERN 1984-86

- 200 GeV/c π^- beam at ~ 1 MHz through centre of detector aperture

- 2 CCDs slipped in between thin tgt and first of 6 Si microstrip detectors, followed by 30 drift chambers

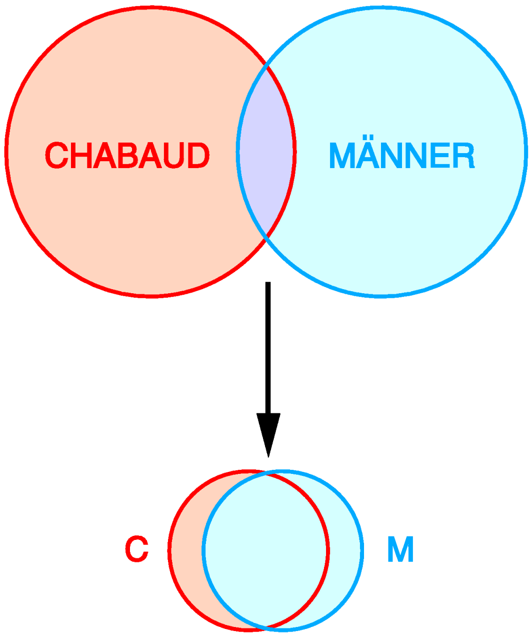




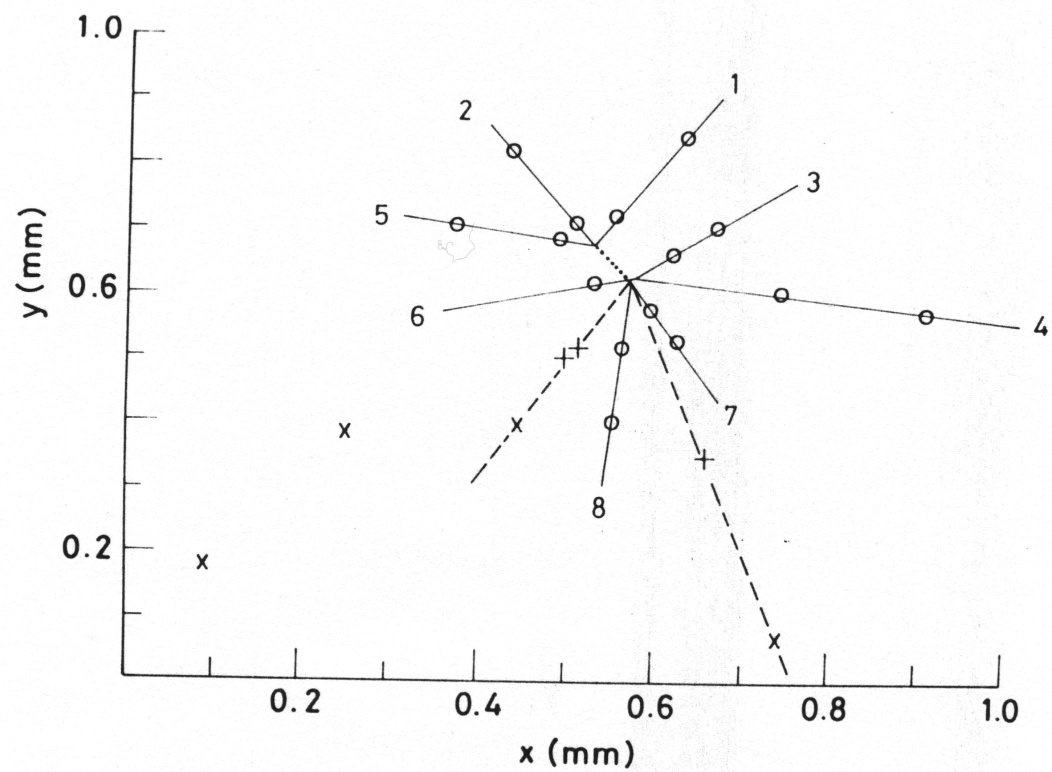
- Strong programme of charm physics including measurement of Ξ_c^0 lifetime

$$0.082^{+0.059}_{-0.030} \times 10^{-12}\,\mathrm{s}$$

6 microstrip planes



2 CCDs added

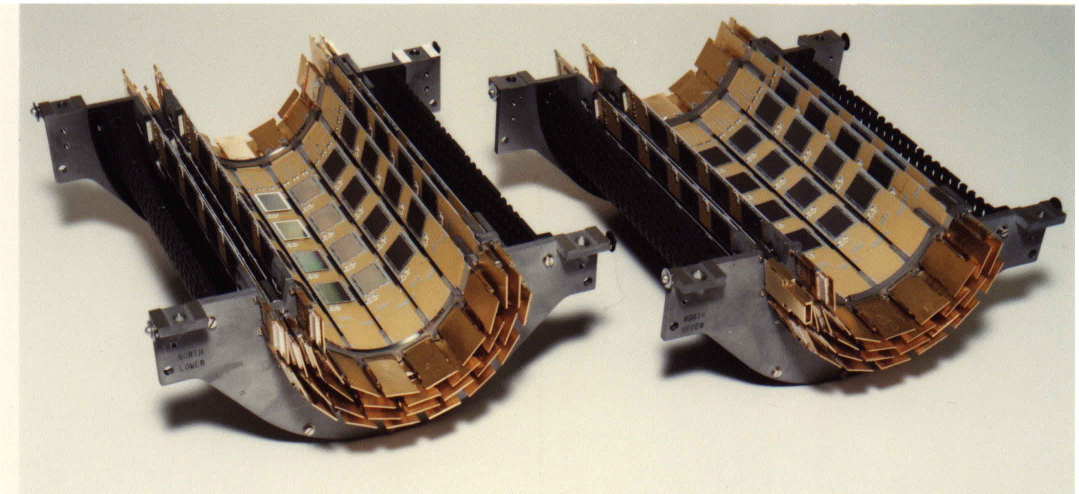


- The transition to a collider experiment (SLD) 5 years later was quite challenging.

The SLD Vertex Detectors

VXD2

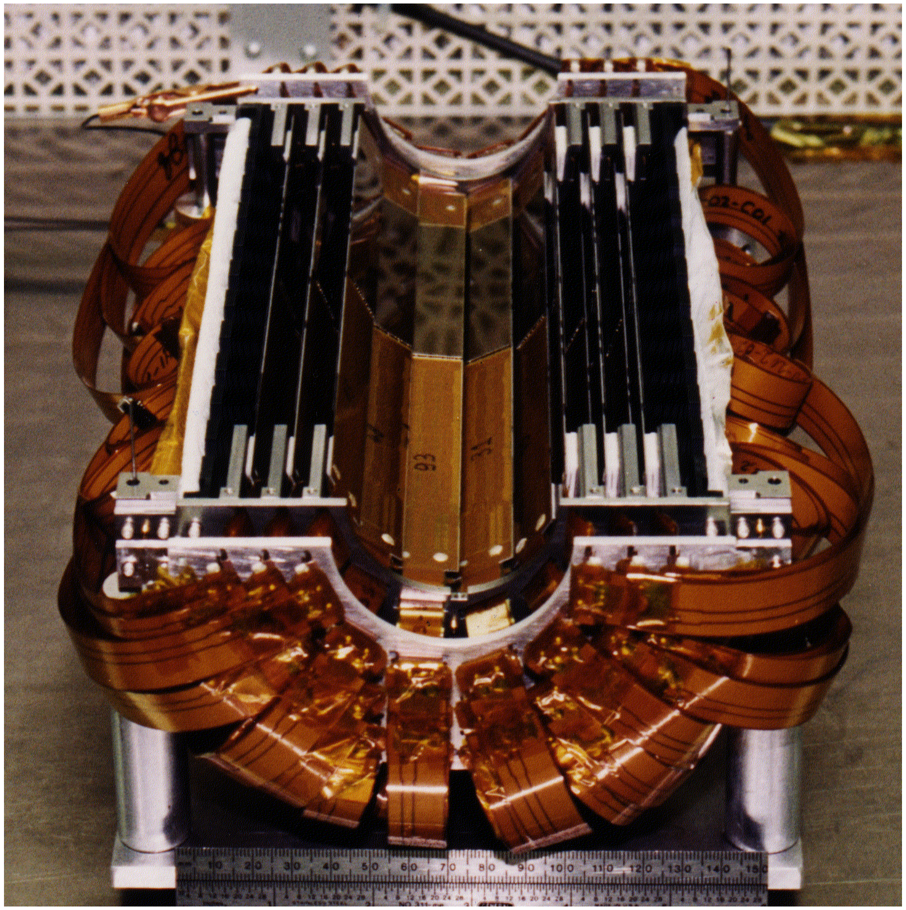
VXD3



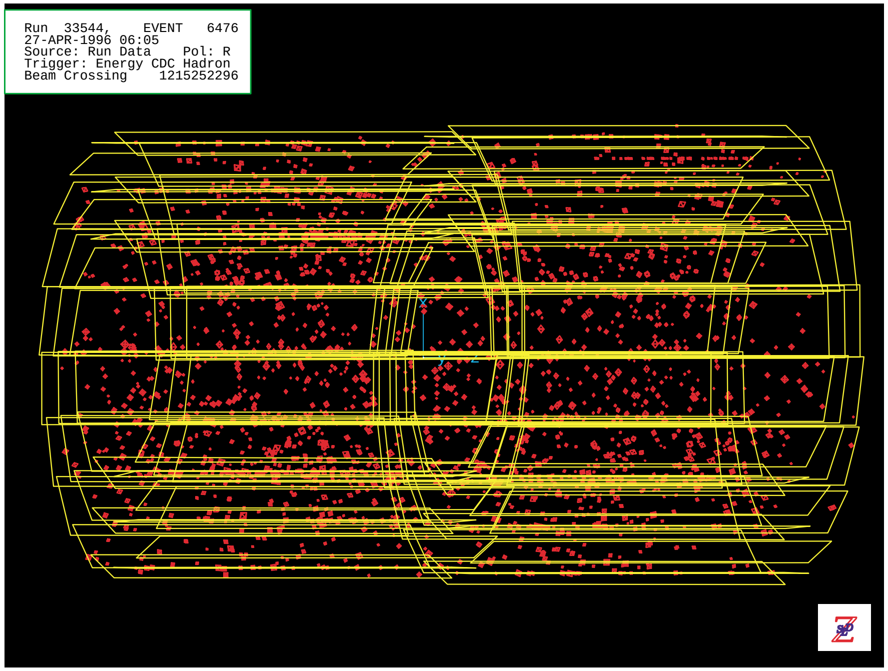
120 Mpixels

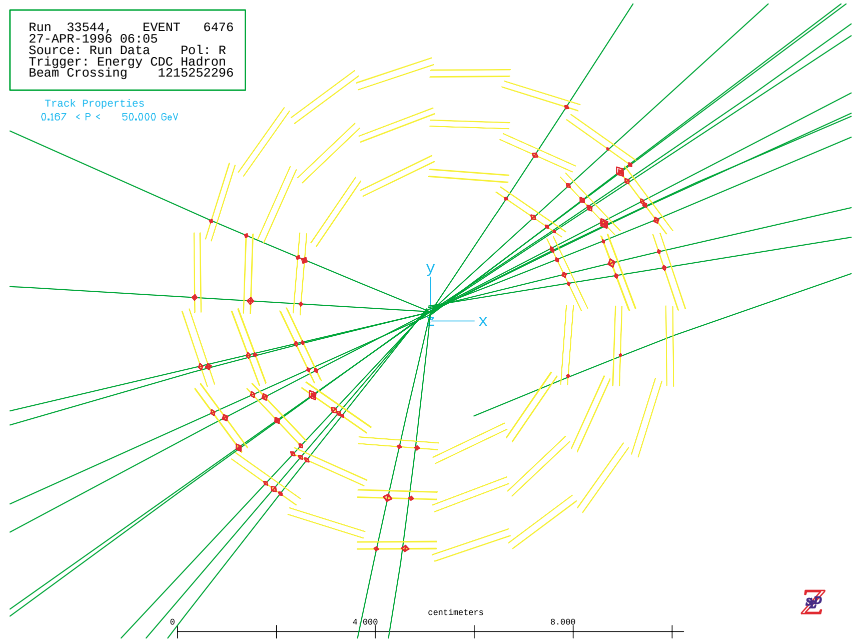
Proc 26th Int Conf on HEP, Dallas TX (1992)

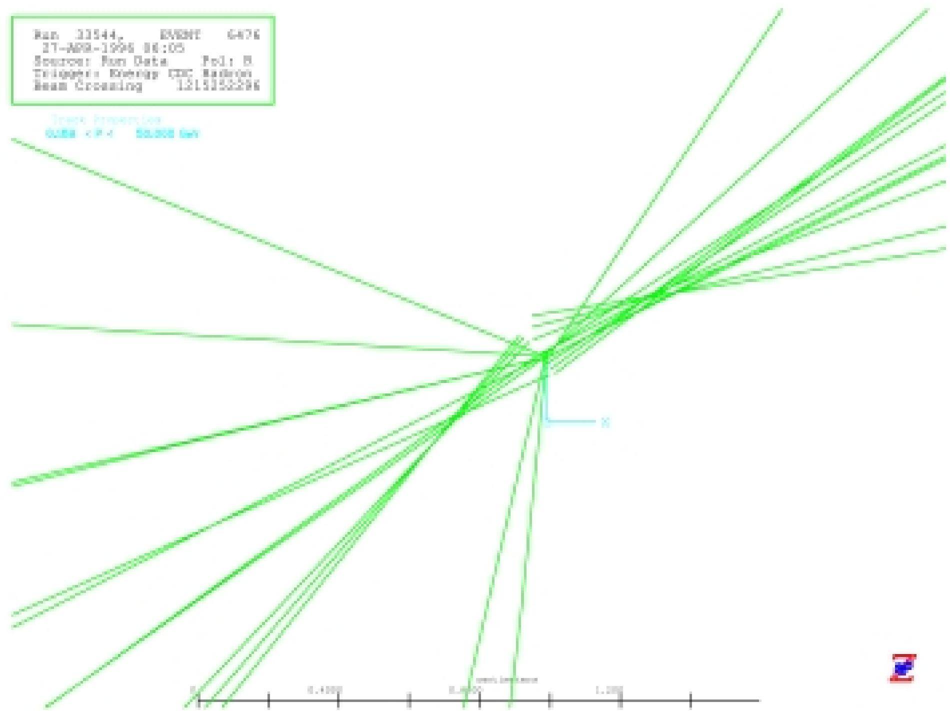
307 Mpixels



NIM A400 (1997) 287







- Saved by shrinking microelectronics/fibre-optics
- Layer thickness 0.4% X_0 (from 1.2% X_0 in VXD2)
- Best imp param resolution of any LEP/SLC expt

$$\sigma_{r\phi} = 9 \oplus \frac{33}{p \sin^{3/2}\theta}\,\mu\text{m}$$

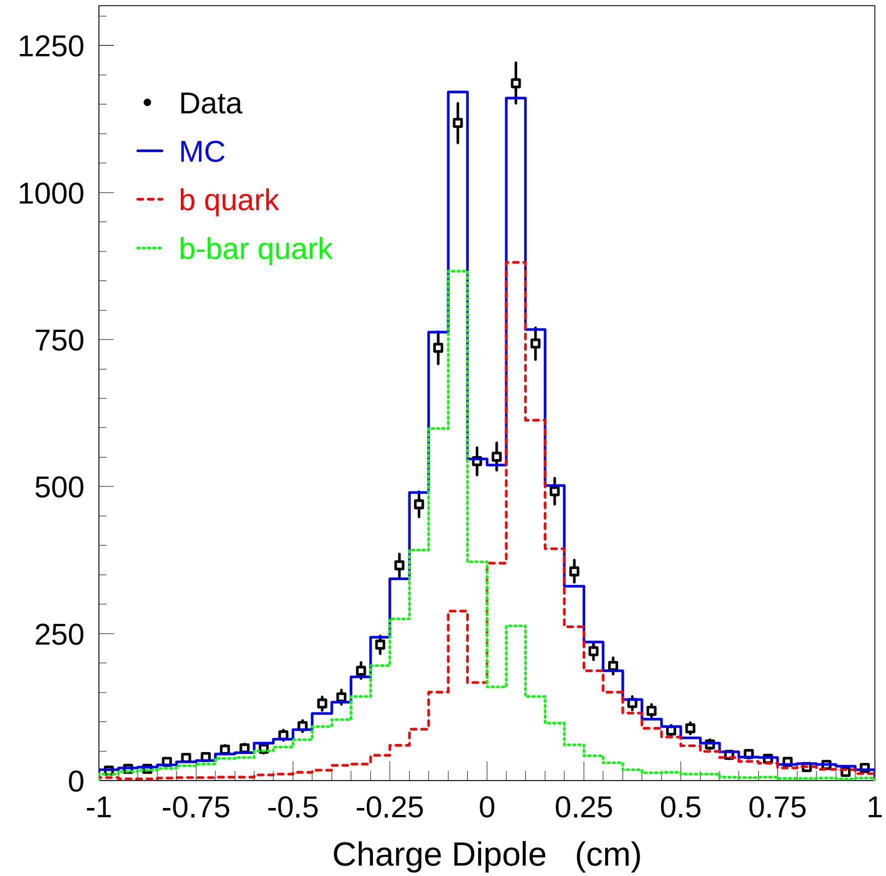
$$\sigma_{rz} = 17 \oplus \frac{33}{p \sin^{3/2}\theta}\,\mu\text{m}$$

Strong programme of b and charm physics, despite having only few percent of the LEP Z sample

- best measurement of $g \to b\bar{b}$
- best measurement of b quark fragmentation
- second most precise measurement of R_b
- best sensitivity to B_s^0 mixing at high Δm_s
- Vertex charge used to distinguish b wrt $\bar{b}$, c wrt $\bar{c}$
- Charge dipole does this for neutral B decays

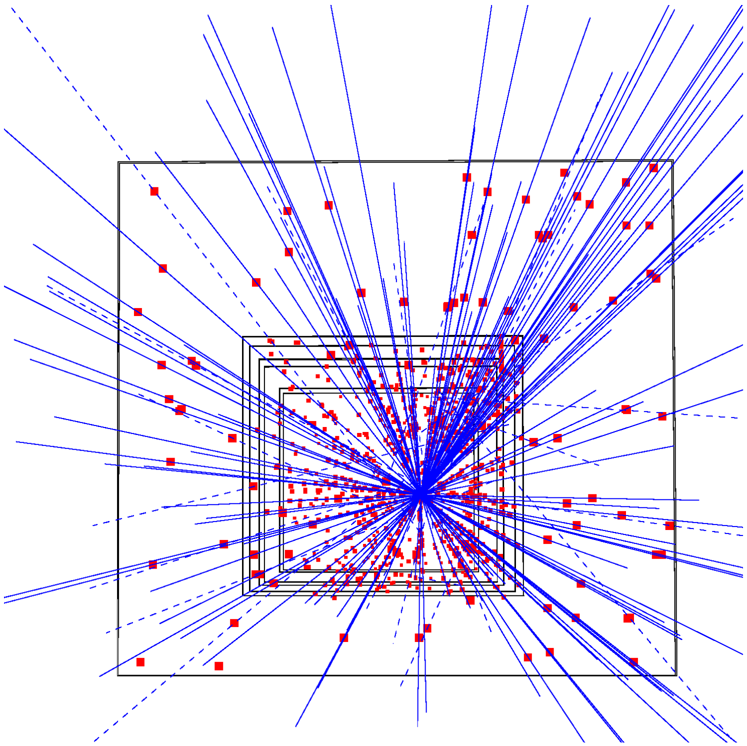
eg $\quad B_s^0 \to D_s^- \pi^+$ [+ve secondary vertex]

$\hookrightarrow K^+ K^- \pi^-$ [-ve tertiary vertex]



SLD Charge dipole

Experiment WA97 at CERN (~1995)

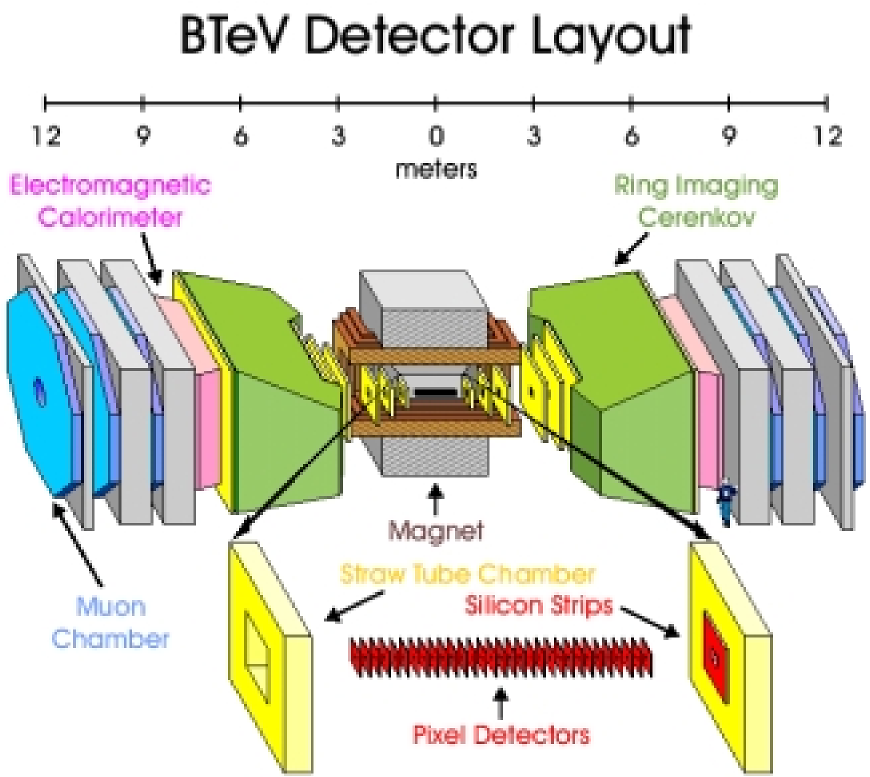


- Pb ion beam on Pb target
- 7-plane hybrid pixel telescope, ~ 0.7 Mpixels
- Very high track multiplicity: 153 tracks in this event
- Established enhancement of Ω^- production wrt Ξ production, evidence for QGP

- Detectors with similar technology operated in DELPHI to improve very forward tracker (VFT)

Future at or near the energy frontier

BTeV



- BTeV and LHCb will eventually take over from the e^+e^- B factories, starting ~ 2005

- BTeV vertex detector will be extremely adventurous
    - 31 triplets (93 planes) of hybrid pixel detectors
    - immersed in a magnetic field of 1.6 T
- Goal is to achieve a *level-1* vertex trigger, never before realised
    - Pixel-based hence *robust* track finding
    - Measured trk momenta, hence robust imp param significance
- topological selection of *B* mesons and hadrons with excellent systematic precision
- Challenges
    - 132 ns BX interval, and 2 interactions on average per BX
- Tools
    - Readout chip delivering 5-10 μm spatial resolution by use of 2-bit ADC in PUC
    - Trigger logic uses 3000 DSPs: ~ 100 μs latency, during which time data are stored in a 1 Tbyte buffer
- Typically require 2 tracks beyond 6σ
    - ~ 74% efficiency for $B_s^0 \to D_s^- \pi^+$, with
    - 99% suppression of minimum bias events

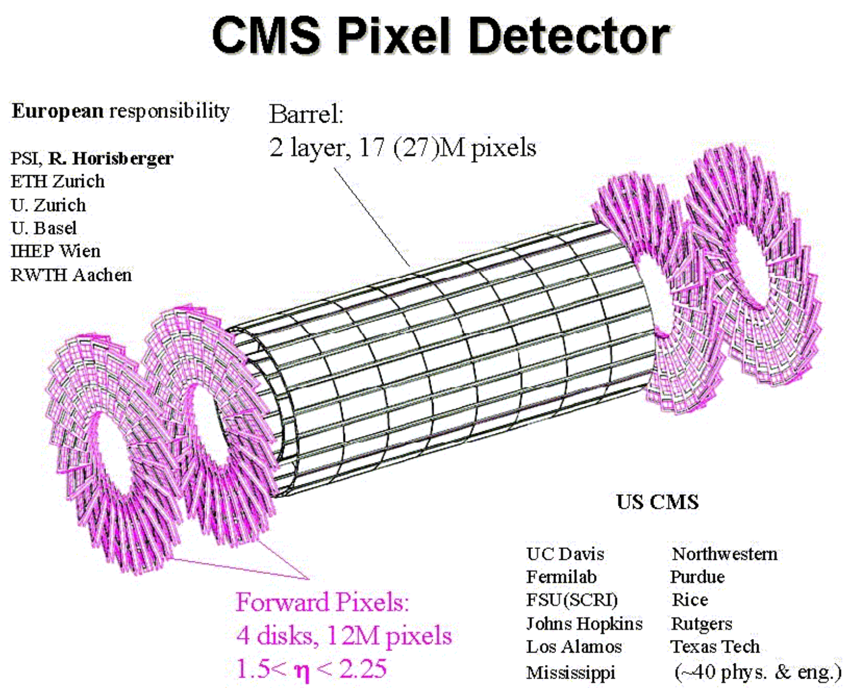
LHC GPDs: ATLAS and CMS

- Physics example, supersymmetric Higgs production

$$gg \to b\bar{b}A \qquad A \to Zh^0 \qquad h^0 \to b\bar{b}$$

(4 or more energetic *b* jets in the event)

- Efficient *b* tag is important
- BX interval 25 ns
  20 interactions /BX
- Early SSC studies were dubious about *any* possible tracking, let alone at small radii
- ~ 4 cm inner layer radius now considered possible

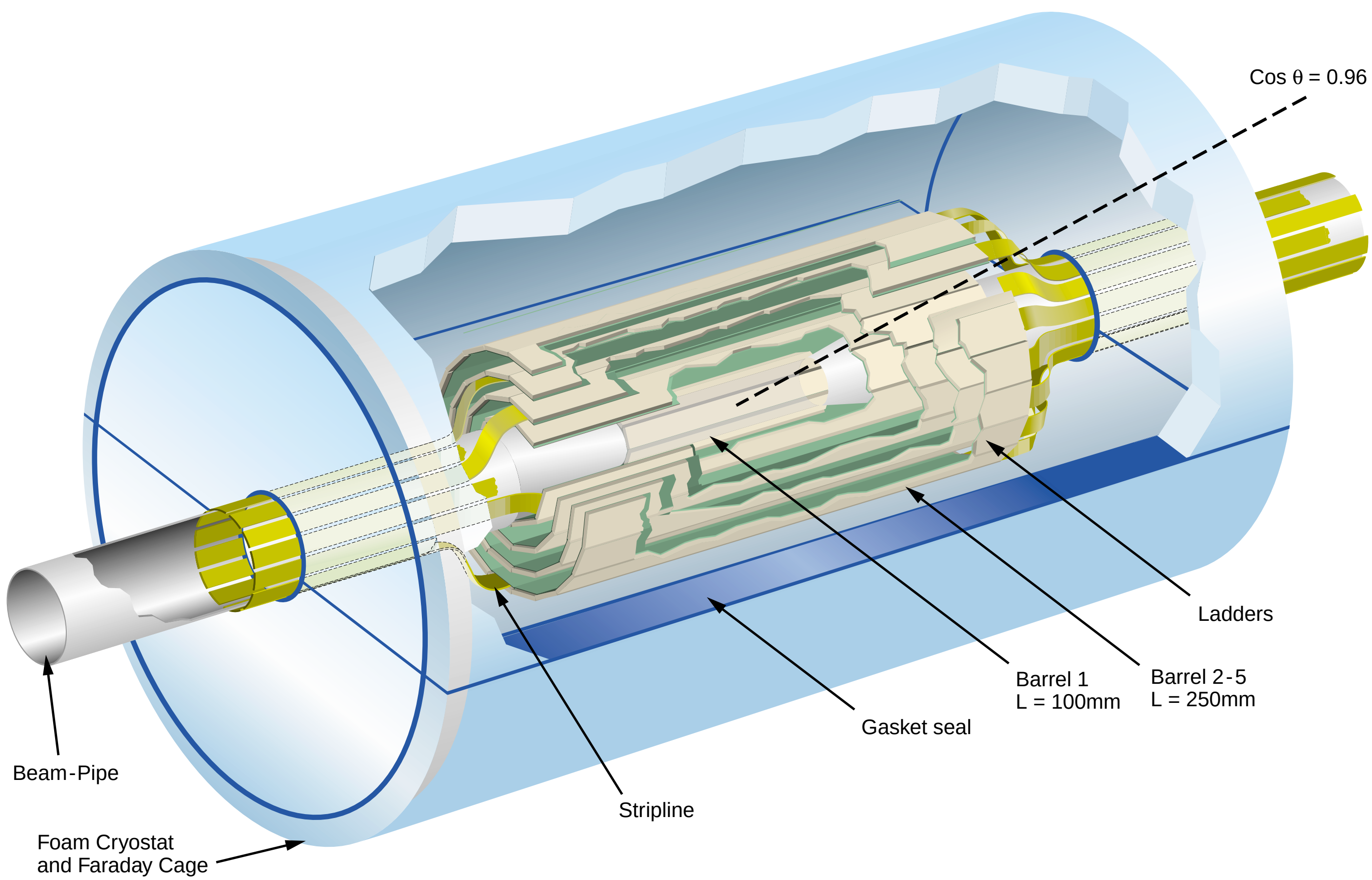


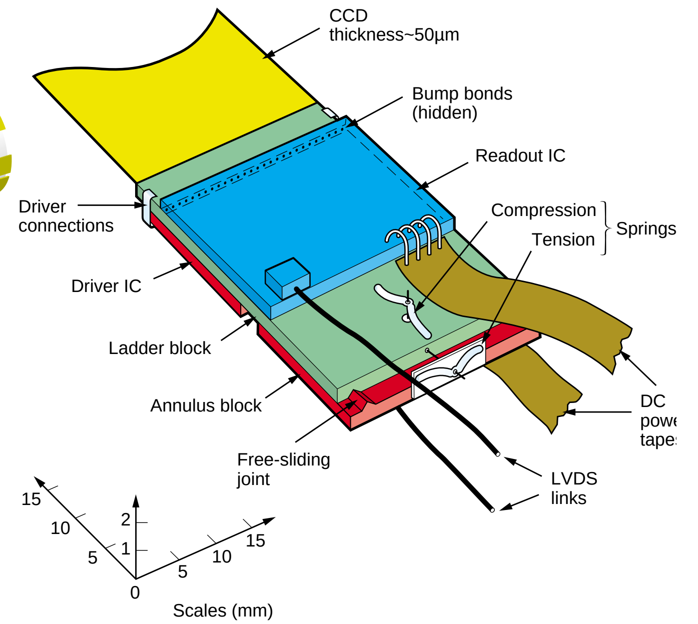
- Compromises (inevitably)
  - Pixel size larger than desirable
  - Complex mechanical assemblies, so cannot be as thin as desirable
  - 60 μW/pixel and 39 Mpixels $\Rightarrow$ 2.3 kW power [3 kW in total]
  - Liquid cooling; pipes and fluid increase the thickness
  - ~ 2% X_0/layer overall
- Performance
  - For *b* jet efficiency ~ 50%, suppress charm/gluon/*uds* jets by factor 10/100/300

Future e^+e^- Linear Collider

Describe the CCD detector option, but monolithic APS (with NMOS or DEPFET charge sensing transistor) may prove competitive

- Unsupported (stretched) silicon option for ladders of 0.06% X_0 thickness





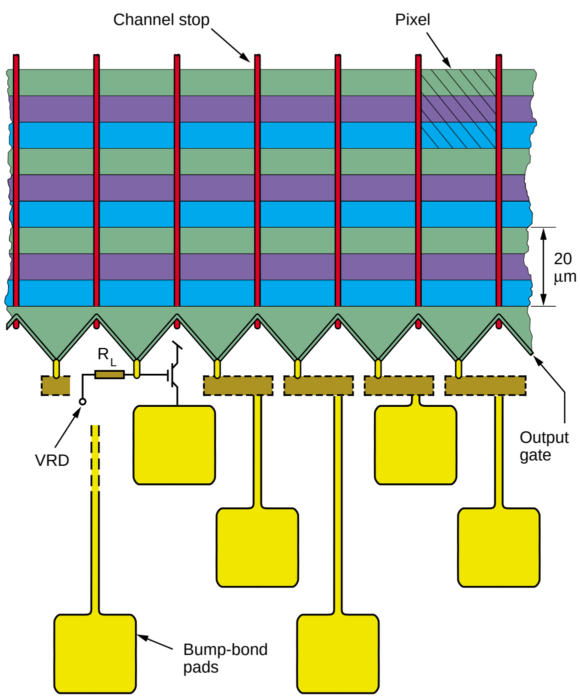
- Layer-1 radius = 15 mm

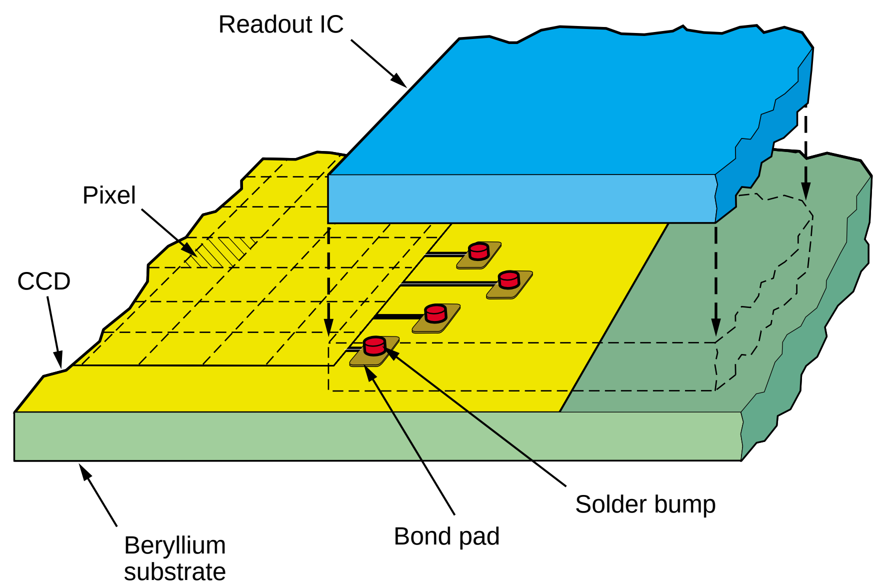
- Pixels $20\times20\ \mu m^2$; total of 800 Mpixels (compared with 307 Mpixels at SLD)

- Need untriggered operation, with full analysis in processor farm, not to miss new physics with subtle signatures (eg non-pointing γ, single low energy pion from chargino-neutralino cascade)

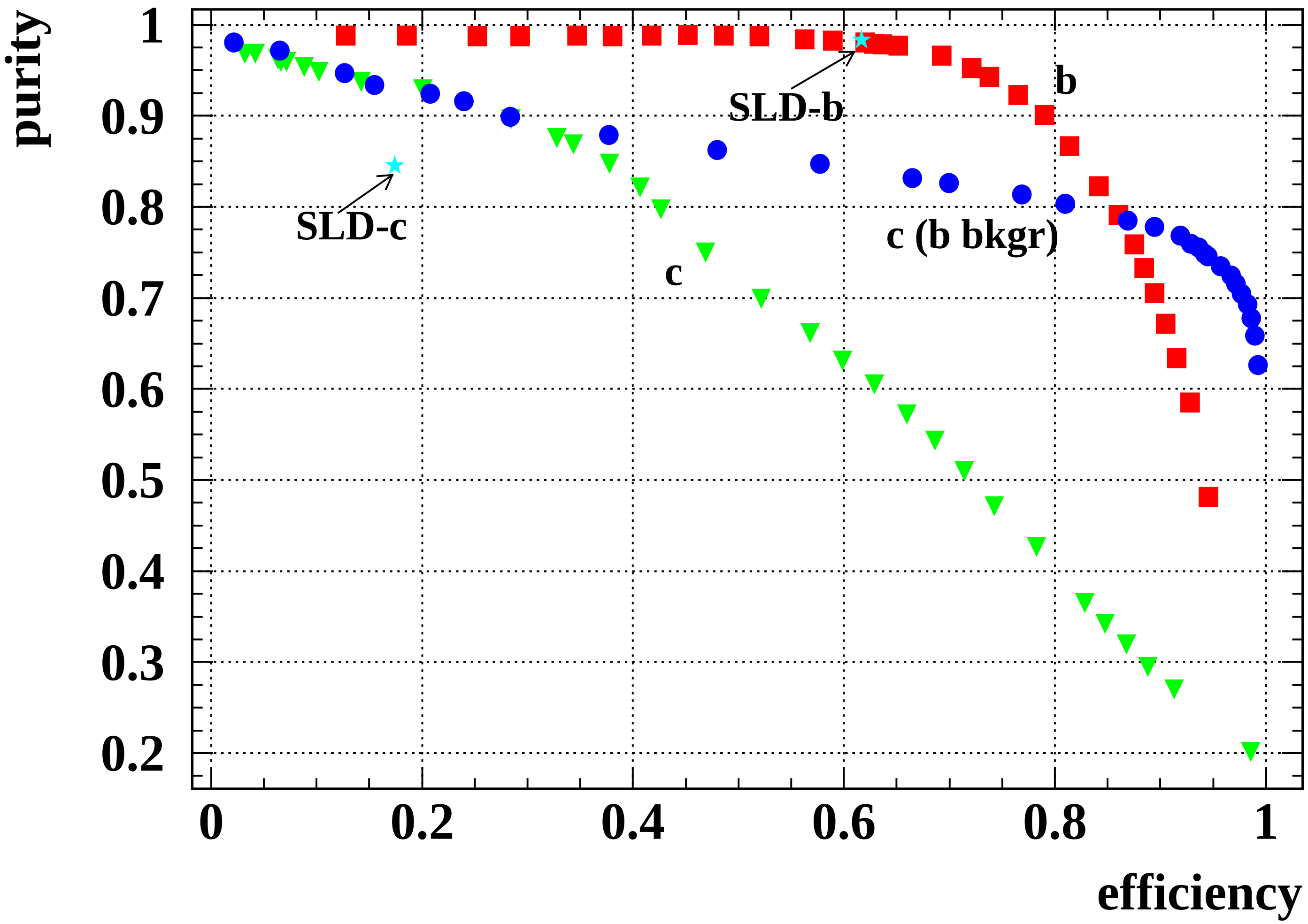
- For TESLA: continuous readout during 950 μs bunch train. With 50 μs readout time, layer-1 hit density is ~ 4/mm^2. This is comfortable

- Column parallel CCD connected to a deep submicron readout chip





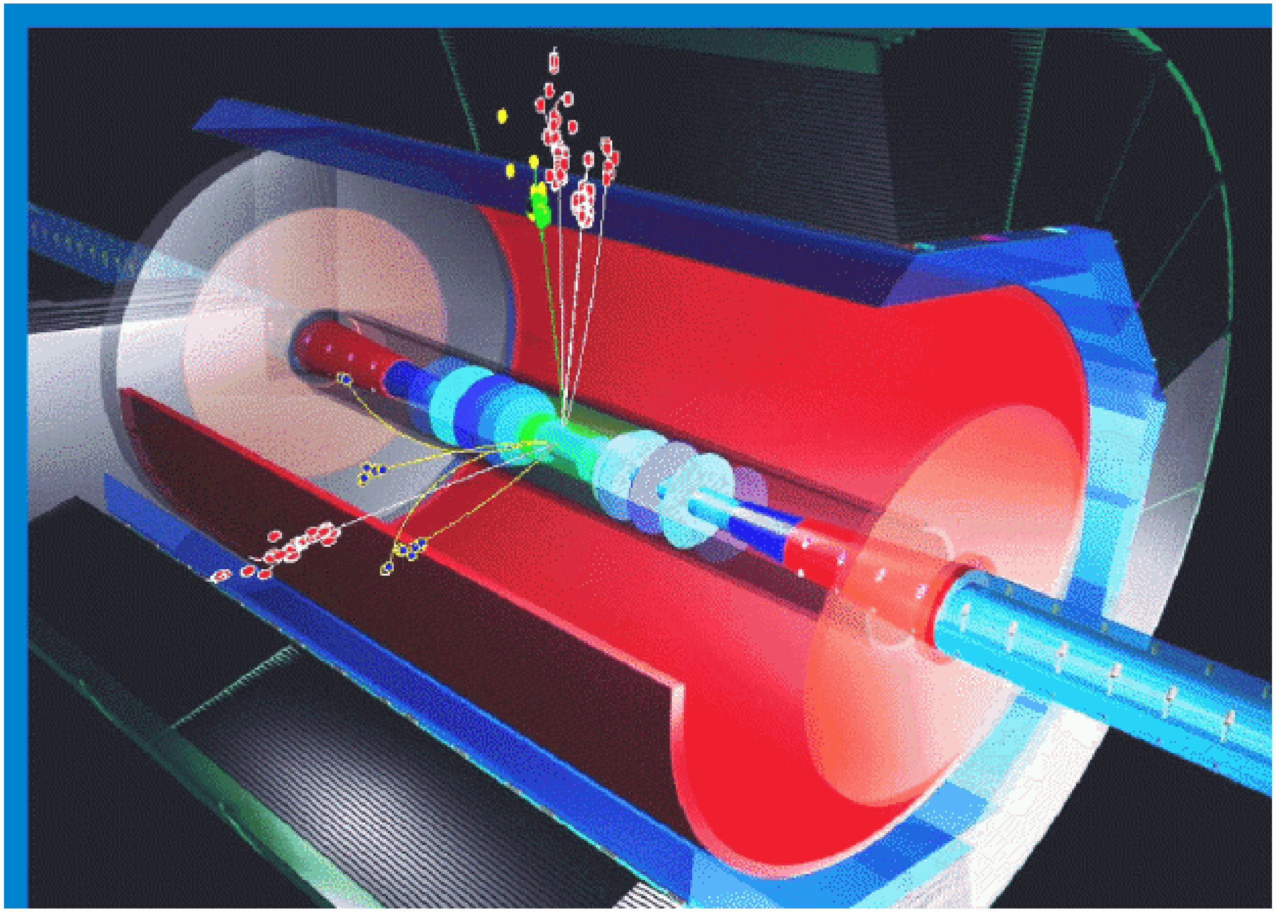
Potential for physics is becoming well established technically



Sefania Xella Hansen et al LC-PHSM-2001-024

- Synergy with ECAL (for highly optimised *energy flow*)

General comment: need for access



- Highly hermetic nested system
- Tempting to be daring, and accept major access problems. Bad idea!
- Possible accidents with beam, need for maintenance and (most important) upgrades
- Painless access for removal and re-installation of vertex detector should be designed in

Other Applications

- Possible applications are about as varied as those of that other pixel detector, the human eye

- Restrict examples to scientific instruments; the major commercial manufacturers are too busy for our small market

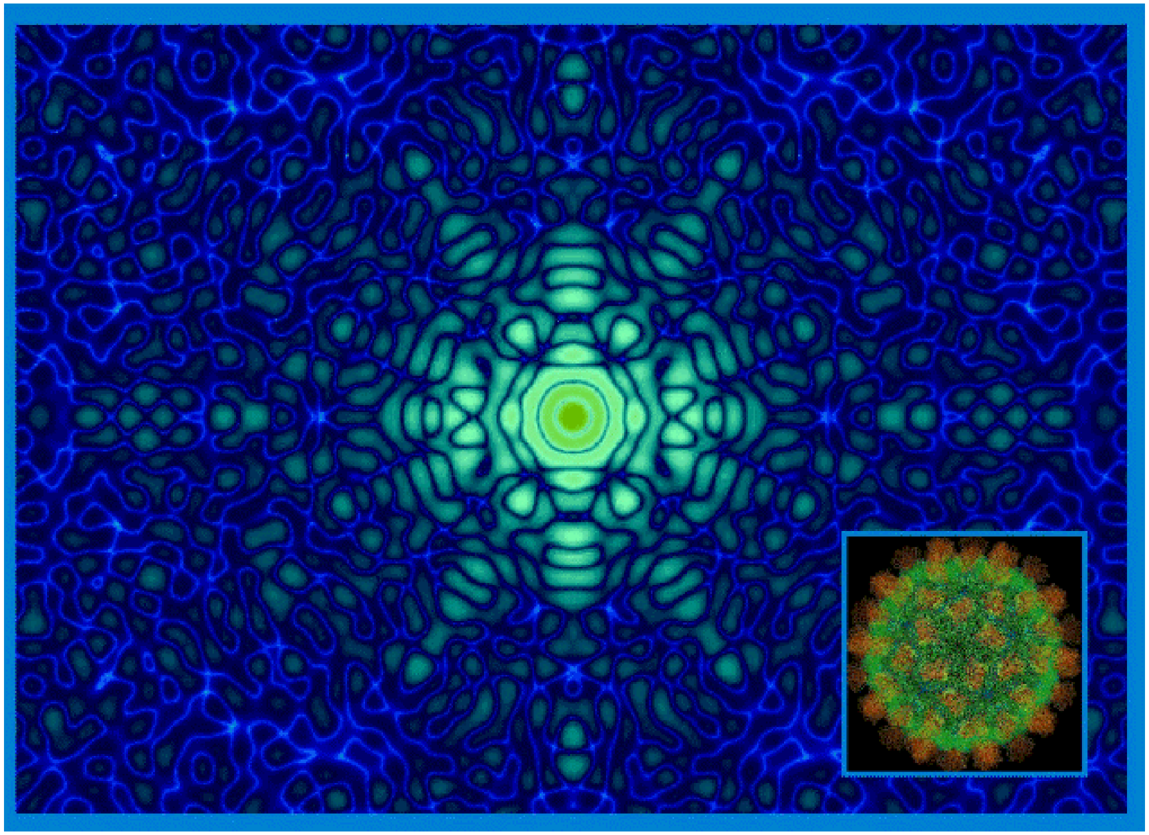
- Areas of major overlap:

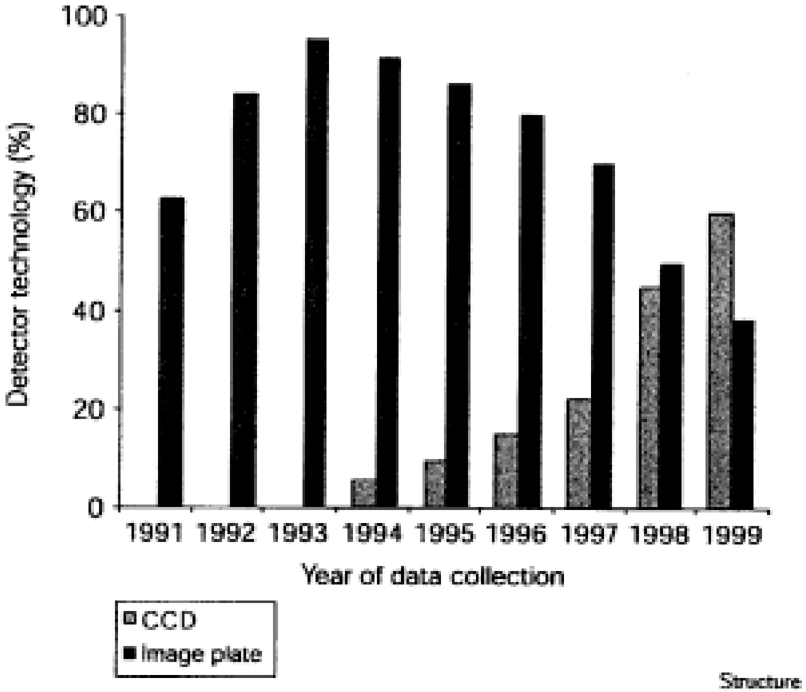
  Astronomy and space-based earth observation
  X-ray crystallography
  Optical and X-ray spectroscopy

- Common requirements:

  larger area
  faster readout
  on-detector data sparsification
  radiation hardness
  thin detectors

- Example from the ‘fall of the wall’ in structural biology (J Hajdu, TESLA Colloquium)





- 120 Hz frame-rate needed at SSRL (with 14 bit dynamic range)

- CCDs have the necessary inter-pixel gain uniformity etc, column parallel architecture will provide the required speed enhancement

- R&D between application areas is a multi-directorial transfer. We particle trackers can gain from others, eg the LLL CCD (24 hour surveillance camera)

Conclusions

- Over the past 20 years, Si detectors have evolved from being an unreliable technological backwater into powerful tools for flavour ID at the energy frontier
- 'Dumb' pixel detectors (CCDs) have provided the highest precision tracking for vertex detectors in fixed target hadron and e^+e^- collider experiments
- 'Smart' active pixel detectors have been used for track reconstruction in high multiplicity events
- With the help of deep submicron readout chips, hybrid APS devices promise to deliver good *b* tagging and even triggering in the *inferno* of TeV-scale hadron colliders (BTeV, ATLAS, CMS)
- For TeV-scale e^+e^- colliders, CCDs and monolithic APS devices (both profiting from the deep submicron technology) promise to deliver unprecedented physics performance
- Other fields of science are enjoying major developments due to rapid progress in these enabling technologies, from structural biology to observing the most distant objects in the universe
- As with microelectronics, silicon-based pixel systems seem likely to dominate the future of scientific imaging, other than hybrid systems for IR or hard X-rays
- However, there is always room for a new idea…

CCDs for particle tracking?

- Some opinions of semiconductor detector experts in 1980:

  - ‘Put such a delicate detector in a beam and you will ruin it’
  - ‘Will work if you collect holes, not electrons’
  - ‘Far too slow to be useful in an experiment’
  - ‘It’s already been tried, didn’t work’
  - ‘It will work but only with ≤ 50% efficiency’
  - ‘To succeed, you will have to learn to custom-build your own CCDs: investment millions’
  - ‘At room temperature it would be easy, but given the need to run cold, the cryogenic problems will be insurmountable’
  - ‘May work in a lab, but the tiny signals will be lost in the noise (RF pickup etc) in an accelerator environment’’

- Fortunately, some other experts were really encouraging and helpful: Veljko Radeka (BNL), Joe Killiany (NRL), Jim Janesick (JPL), Emilio Gatti (Milano), David Burt (GEC), Wrangy Kandiah (AERE Harwell), Pier Francesco Manfredi (Pavia), Herb Gursky (Harvard Smithsonian)

- By July 1980, we took the plunge. Very much a group decision, since it was a major project with rather few people.

SLC Detector Workshop 1982

- Silicon detectors were notoriously unreliable, regarded as unlikely candidates for a collider vertex detector

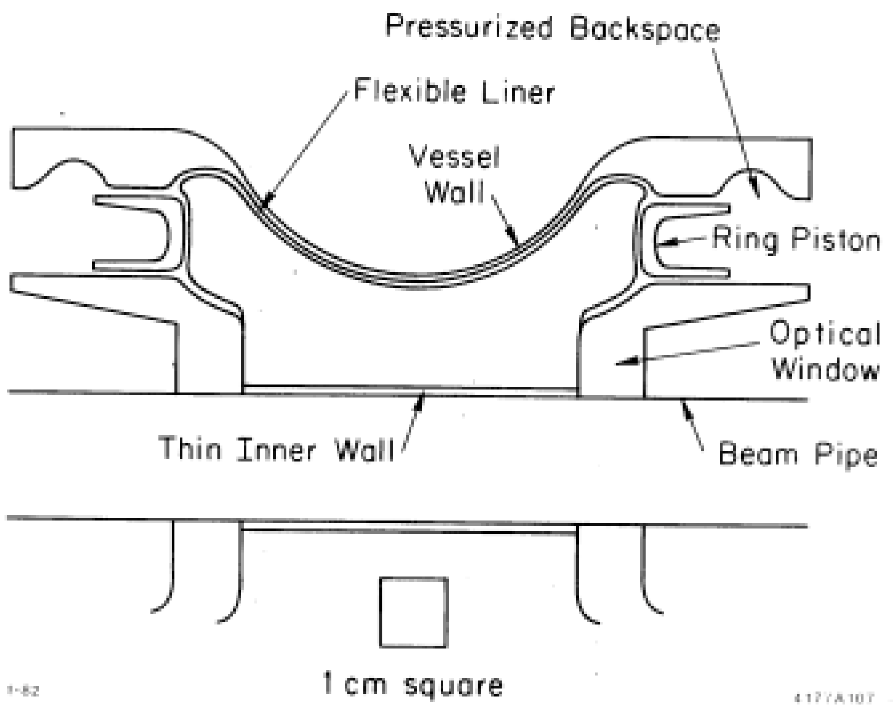


Fig. 7. Conceptual design of a propane bubble chamber vertex detector.

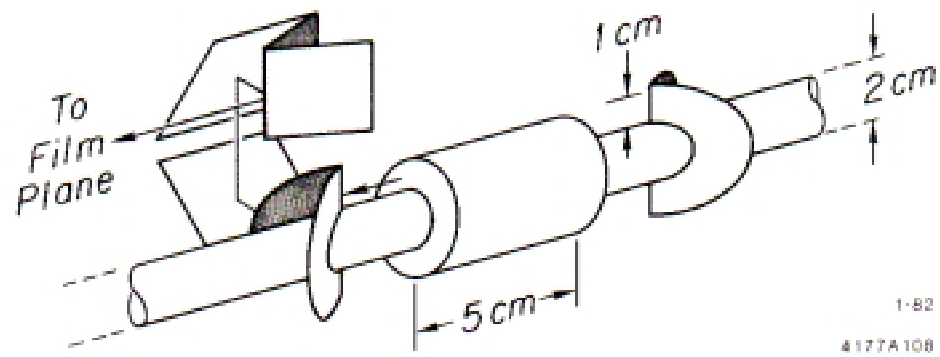


Fig. 8. Illumination of a bubble chamber vertex detector.

No material budget, but Uriel wouldn't have liked it!

[What will we *really* be using in 2020?]